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The city and urban heat islands: A review of strategies to mitigate adverse effects

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ABSTRACT

Cities occupy 2% of the earth's surface but their inhabitants consume 75% of the world's energy resources. Under certain conditions, the heat from solar radiation and different urban activities can make city temperatures rise in certain areas, simply because of the way in which a city is structured. This effect is known as the urban heat island (UHI). This article provides a review of recent research on the urban heat island as well as of the strategies that can be applied to mitigate its adverse effects. Such strategies can be applied in the project design phase of urban planning and thus directly affect city temperatures on a local scale. The elements analyzed in this paper include green spaces, trees, albedo, pavement surfaces, vegetation, as well as building types and materials. The discussion of this research clearly reflects the impact of urban morphology on local temperatures and how urban design can be modified to reduce energy consumption and CO_2 emissions into the atmosphere. This study is useful for professionals who are responsible for decision-making during the design phase of urban planning.

Contents

1. Introduction

Cities occupy approximately 2% of the earth's surface. In the world today, urban populations are rapidly increasing in size and complexity because more and more people are leaving rural areas to migrate to cities [1]. Precisely because of their rising population, cities require large quantities of energy to function properly. In fact, city dwellers consume over 75% of the total energy resources as a result of activities carried out in the urban environment [1]. Part of this energy is dissipated in the form of heat, which is intensified by solar radiation. Under certain conditions, this heat accumulates since it is entrapped by urban structures, and then at night, slowly dissipates. This creates an effect known as a *heat island*, which can raise temperatures in densely built-up urban

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zones. When there is a lack of green spaces, this effect is even more accentuated as a consequence of greenhouse gas emissions [2]. The temperature increase caused by the heat island reduces the need for heating in the winter, but in a parallel way, increases the cooling demand in the summer.

Kolokotroni analyzed the heat island in London. She found that the cooling load in the city was 25% higher than in rural environments, whereas the heating load diminished by 22% [3]. However, this widespread use of air conditioning systems consumed a larger quantity of energy, and had a negative impact both on the economy and the environment.

Santamouris et al. analyzed the impact of urban climate on energy consumption in Athens. In this city, the mean intensity of the heat island exceeds 10 °C. This study concluded that as a consequence of this effect, the energy required to cool urban buildings increased twofold, and the peak electricity load for cooling increased threefold. This was especially true for higher set point temperatures, whereas the minimum coefficient of performance (COP) value for air conditioners fell by as much as 25% because of high ambient temperatures. During the winter months, the heating load of downtown urban buildings decreased by 30% [4].

Kolokotroni et al. presented the results of a computational study of energy consumption and related CO_2 emissions for the heating and cooling of an office building in the London heat island. These authors found that heating loads decreased whereas cooling loads and overheating hours soared. Their conclusion was that this could quintuple CO_2 emissions for the city of London by 2050 [5]. Kondo and Kikegawa estimated temperature sensitivity to the peak electricity demand to be 6.6%/°C [6] for the most densely urbanized zone of Tokyo. Regarding the environment, such temperature increases were found to favor the reactions of combustion gases in the atmosphere. In some cases, this could even modify the regional climate as a consequence of temperature changes in the city.

Many research studies have focused on the heat island effect. For example, Okeil analyzed solar exposure in winter and the reduction of solar gains in winter with the implementation of strategies that mitigated the heat island effect. In this study, the concept of the Residential Solar Block (RSB)[1] was applied. The results showed that RSB favors strategies for counteracting the urban heat island through increased airflow between buildings, the use of green roofs, and the reduction of transportation energy [7].

Taha reviewed certain characteristics of urban climates and the causes of the heat island effect. In particular, this study was on the impact of surface albedo, evapotranspiration, and anthropogenic heating on the urban climate[2]. He demonstrated that vegetation cover generated favorable conditions for evapotranspiration and created oases that were 2–8 °C cooler than their surroundings [8].

Hirano and Fujita devised a method to evaluate the impact of the heat island effect. Their method took into account the temporal and spatial distribution of energy consumption as well as air temperature. This study focused on primary energy consumption for heating buildings and water as well as for cooling in the commercial and residential sector. The results demonstrated that the urban heat island increased energy consumption in the commercial sector, but reduced consumption in the residential sector. It was concluded that measures to mitigate the urban heat island effect should be applied to the city center where there are more commercial buildings, but without neglecting the residential sector [9]. Kikegawa et al. quantified the impact of countermeasures against urban heat islands on the energy consumption of buildings in Tokyo during the summer months [10].

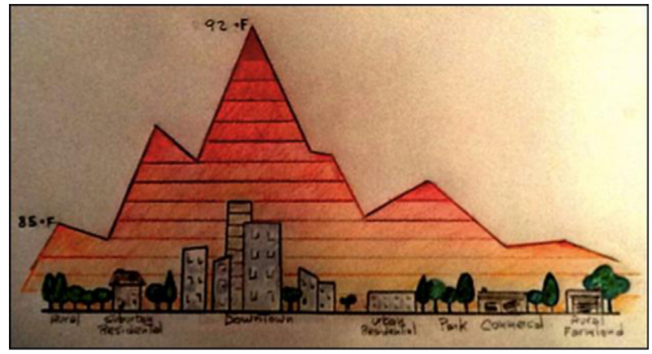


Fig. 1. Changes in land cover can affect surface and air temperatures.
Source: Drawing by M. Gago.

Kolokotroni et al. presented the results of air temperature measurements taken in 1999 and 2000, with which they calculated the intensity of the heat island in the city of London. The effect of the temperature increase due to this heat island was analyzed in relation to the effectiveness of stack night ventilation in office buildings [11].

Giridharan et al. studied the impact of design-related variables on the urban heat island. According to this research, differences in outdoor temperatures inside a residential development and between developments could be explained by the effect of such variables on the overall environment [12]. They found that the city had the capacity to modify local climate, and even created environmental conditions that could be regarded an urban micro-climate. The most prominent features of this micro-climate were the following:

- A temperature increase (see Fig. 1).
- A reduction in the daily temperature range.
- A distinctive wind distribution in the city resulting from friction with buildings and the channeling of airflows through the streets.
- A water budget that differs from that in rural environments.

According to Wong et al., there are three elements that affect urban temperature on a local scale: buildings, green spaces, and pavement [13].

The implementation of measures to counteract or mitigate the heat island effect depends on a wide range of factors, some of which can be incorporated into urban planning strategies [14–20], whereas others are outside the scope of the controlled use and geometry of spaces. Jusuf et al. studied the influence of land use types on the heat island in the city of Singapore. They identified different land uses and analyzed their effect on the higher ambient temperature in the city. This research underlined the importance of land use planning in determining the quality of surroundings [14]. According to Rosales, effective strategies can be developed that improve the long-term sustainability of cities, thanks to the use of sustainability indicators (i.e. ecological footprint, quality of life, city development, urban governance, and the Gini coefficient[3]) in the urban planning process [17].

[1] RSB is the building form developed with the aim of achieving the functional, spatial, social and visual advantages of the conventional residential block with the energy efficiency advantages of the linear urban form. It is an attempt to generate the maximum built-up volume of the block after putting overshadowing restrictions on the site.

[2] Albedo is the fraction of incident radiation that is reflected by a surface or body. Light surfaces have higher albedo values than darker ones, and shiny surfaces have higher values than opaque ones.

[3] The Gini index measures the extent to which the distribution of income or consumption expenditure among individuals or households within an economy deviates from a perfectly equal distribution. A Lorenz curve plots the cumulative percentages of total income received against the cumulative number of recipients

Shudo et al. analyzed the connection between air temperature and land uses based on data collected in Hokkaido, a city in northern Japan. They concluded that throughout the year, urban areas had a warming effect of approximately 2 °C in their mean and minimum temperatures. In contrast, farmlands, woodlands, and forests had a cooling effect, whereas areas by or near the water tended to have a higher minimum temperature [21].

Measures can be applied to counteract or mitigate the heat island effect on urban elements that influence the local temperature. In this case, certain parameters can be used to evaluate the impact of the modification of urban morphology on energy consumption. These results are conducive to the reduction of CO_2 emissions into the atmosphere [13,22]. Examples of these parameters are the following:

- green plot ratio;
- sky view factor;
- building density;
- wall surface area;
- pavement area;
- albedo.

Sadownik and Jaccard proposed a set of urban development strategies based on more sustainable energy consumption. However, factors such as political and institutional problems in land use planning, the siting and design of buildings, alternative energy supply, and transportation management are obstacles to the implementation of these strategies. These authors studied the case of China, and concluded that by 2015, these strategies could reduce emissions in the residential sector and from transportation by approximately 14% for CO_2, 10% for SO_2, 40% for NO_x, and 14% for particle emissions [23].

2. Selection of research studies

This paper systematically reviews recent research on the effects of various planning strategies to counteract or mitigate the heat island effect in the urban environment. The main objective of such strategies is to reduce energy consumption in cities as well as greenhouse gas emissions into the atmosphere. The methodology used for this systematic review work is described in [24,25], and consists of the following steps:

- Exhaustive search of the literature by applying pre-defined criteria for the identification of the most relevant articles in the field.
- Critical evaluation of the quality of the selected articles by synthesizing their content and summarizing the results and conclusions.

For this research, the data were obtained by searching databases of different disciplines (e.g. environmental studies and public health). The search engines used were those on Internet and environmental web pages. The key words for the searches were *temperature, climate change, urban planning, heat island, pollution*, and *CO_2 emissions*. The inclusion criteria for articles were explicitly defined in consonance with the characteristics of the study. To be included in the review, the article had to be an in-depth study of the heat island effect, its characteristics, influential factors, consequences, mitigation strategies, effects on human health and environment, etc.

The structure of this review reflects the inventory of possible strategies to mitigate the urban heat island effect. These strategies were identified by analyzing the contents of the articles. However, in reference to the heat island effect, it should be underlined that these strategies tend to overlap because of their interrelation, and also because many of the research studies simultaneously implement several of them. The articles analyzed in the review were retrieved from the following data bases: *Journal Citation Reports*, *Web of Knowledge*, *Web of Science*, and *Scopus*. From each article, we extracted the research objectives, the description of the methodology applied or developed, the geographical location of the study, theoretical premises, computer tools used, and above all, the information in the conclusions regarding the mitigation of the urban heat island effect.

3. Planning strategies for the mitigation of the heat island effect (I): green spaces and trees, albedo, and pavements

High summer temperatures in the urban heat island increase energy use for cooling and accelerate the formation of smog. Except in outlying areas of the city, in summer, the heat island effect is mainly due to the lack of greenery and the high level of solar radiation absorbed by the urban surface. An analysis to discover temperature trends over the last 100 years in various cities in the United States showed that since 1940, temperatures in urban areas had risen 0.5–3 °C. Accordingly, the electricity demand in cities went up 2–4% for each degree celcius of temperature increase.

Green roofs, cold pavements, and green spaces in urban areas are all measures that favor the cooling of surfaces and contribute to the reduction of energy consumption [26,27]. In fact, various authors propose urban greening as a strategy to mitigate the consequences of higher temperatures due to the heat island effect [28,29]. Urban greening moderates temperatures and favors processes such as evapotranspiration and the shading of surfaces.

Evapotranspiration is a key process that describes the water loss of a plant in the form of vapor released into the air. This occurs when energy is conveyed to a surface capable of evaporating water if the relative humidity is less than 100%. Since this energy is obtained from sunlight, the yearly and daily evolution of evapotranspiration depends on that of solar radiation. Evapotranspiration produces the cooling of leaves and the air temperature around them [30]. This contrasts with the effect of impermeable urban materials, such as asphalt and concrete, which do not retain water for evaporation. On the contrary, these materials rapidly absorb water and retain heat when they are exposed to solar radiation.

In addition to cooling by evaporation, the shading from trees can also cool the atmosphere, simply by intercepting solar radiation and thus preventing the heating of the ground surface as well as the air [30–33]. As for the use of green spaces and trees to mitigate the heat island effect, the research can be categorized in terms of the effect produced by the following elements:

- Parks and green areas;
- trees and vegetation;
- green roofs;
- pavement;
- Albedo.

3.1. Parks and green areas

According to Shashua-Bar and Hoffman, in parks and green areas, the combined effects of evapotranspiration and shading

(*footnote continued*)
starting with the poorest individual or household. The Gini index measures the area between the Lorenz curve and a hypothetical line of absolute equality, expressed as a percentage of the maximum area under the line. Thus, a Gini index of 0 represents perfect equality, while an index of 100 implies perfect inequality. http://data.worldbank.org/indicator/SI.POV.GINI.

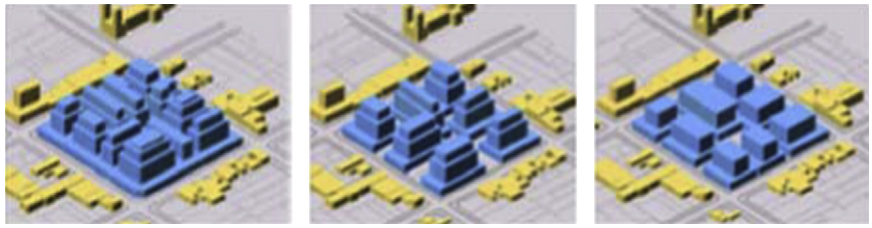


Fig. 2. (a) Outline of analyzed block of buildings, maximum density possible according to the CUE of the Capital City. (b) Alternative outline 2, building height 25 m, and maximum density possible according to natural illumination availability. (c) Alternative outline 1, building height 15 m, and maximum density possible according to natural illumination availability [72].

cause a significant decrease in temperature, and even create what are known as cool islands in the city [34]. Various studies have analyzed the temperature in parks and beneath trees. The general conclusion was that green spaces were cooler than spaces without any greenery [29,35–39]. Eliasson showed that the mean air temperature difference between the park and the city center was as high as 4 °C [40].

Other authors studied this temperature variation not only in green spaces, but also in the commercial areas surrounding them. Thus, Yu and Hien found that in Singapore, the cooling effects of green spaces in the city were significant, not only in parks, but also in the city zones near them. The results showed that vegetation could produce energy savings and reduce the cooling load of buildings by as much as 10% [42].

Ca et al. collected field data to quantify the effect of a park on the summer climate in a nearby area. They analyzed ways to reduce the energy consumed for air conditioning. The air temperature, relative humidity, and other meteorological factors were measured at various locations within the park and in neighboring areas. The study was carried out in the park in Tama New York, a coastal city in the metropolitan area of Tokyo. The results obtained indicated that vegetation significantly modified the city climate. At noon, the temperature reduction was as much as 1.5 °C in a busy commercial area 1 km downwind. This led to a significant decrease in cooling energy consumption in the commercial area [41].

The research analyzed concluded that parks and green spaces could help to mitigate urban heat island effects and decrease cooling energy consumption in summer. Furthermore, it was found that such green spaces also reduced the temperature changes produced by building materials. The research analyzed generally concluded that parks and green spaces could help to mitigate the effects of the urban heat island and reduce energy consumption for the cooling of buildings in summer, besides stabilizing the temperature fluctuation caused by building materials [42,43]. However, it was not clear exactly how park affected the formation of the heat island. The cooling effect seemed to depend on the size of the park and the seasonal radiation conditions, but there was no linear relation between the size of the park and the intensity of the cool island. This intensity was mainly determined by the area occupied by the trees and shrubbery in the park as well as by the shape of the park. Grass was found to have a negative impact on the formation of the cool island.

Cao et al. proposed a park vegetation and shape index (PVSI), which could be used to predict the intensity of the cool island in parks [43]. This could help urban planners to better understand the formation of cool islands and thus be able to design cooler parks that counteract the effects of the urban heat island.

3.2. Trees and vegetation

Various authors analyzed the reduction of energy consumption caused by vegetation and tree shade [44–47] (see Fig. 2). Robitu et al. showed that it was possible to save up to 10% in cooling buildings, simply from the temperature reduction caused by vegetation. This temperature reduction was estimated at 3–5 °K [31]. Akbari et al. monitored the power peak and the energy savings in cooling produced by tree shade in two houses in Sacramento, California. The data collected included air-conditioning electricity use, roof and ceiling surface temperatures, inside and outside wall temperatures, insolation, wind speed and direction, indoor and outdoor dry bulb temperatures, and humidities. Shade trees at the two houses yielded seasonal cooling energy savings of 30%, corresponding to mean average daily savings of 3.6 and 8 kWh/d. It was found that the shade from trees reduced the temperature of outer building surfaces as effectively as the wind speed [48].

Other authors examined the influence of greenery on building design and urban planning [32,49,50]. Ong proposed a new kind of architecture that is known as a *planning metric* for green spaces of cities and buildings. The objective was to determine the optimal levels of the green plot ratio (GPR)[4] for different land uses and for the development of design guidelines. These optimal levels were compared with the current levels of greenery for each type of land use. These studies proposed a leaf area index (LAI) of 1.36–10 for the lawns, shrubs, and full-grown trees with a dense canopy. These values were useful to compensate the loss of green spaces stemming from urban development. Instead of focusing on the discovery of new technologies to combat the effects of climate change and global warming, it is also crucial to have new and insightful ideas regarding the green revolution in architecture and urban planning on a scale that goes from individual buildings to entire cities. According to Ong, the Green Plot Ratio (GPR) is an effective way to facilitate sustainable urban development [51].

Wong et al. simulated the effects of vertical greenery systems on the temperature and energy consumption of buildings. The results obtained showed that 100% greenery coverage from vertical greenery systems was effective in lowering the mean radiant temperature of a glass façade building. Furthermore, it was found that to significantly lower the energy cooling load, the shading coefficient of plant species had to be low. In fact, there is a linear correlation between the shading coefficient and leaf area index such that a lower shading index leads to a greater thermal insulation. Accordingly, a 50% greenery coverage from a vertical greenery system and a shading coefficient of 0.041 reduced the envelope thermal transfer value (ETTV) of a glass façade by 40.68%. The increase of greenery coverage from vertical greenery systems was most significantly felt with a drop in the minimum estate air temperature throughout a large region of the estate [52].

[4] This new metric, the green plot ratio (GPR), is based on a common biological parameter called the leaf area index (LAI), which is defined as the single-side leaf area per unit ground area. The green plot ratio is simply the average LAI of the greenery on site and is presented as a ratio that is similar to the building plot ratio (BPR) currently in use in many cities to control maximum allowable built-up floor area in a building development. GPR allows more precise regulation of greenery on site without excluding a corresponding portion of the site from building development.

Moreover, research has demonstrated that trees and vegetation can also negatively affect the urban microclimate in cold climates. McPherson et al. used computer simulations to study the effect of vegetation on space heating and cooling by analyzing irradiation and wind reduction. They focused on four cities in the USA, which are representative of four different climates. The results showed that in cold climates, dense shade, as in conifers, increased heating costs up to 21% but shade from leafless deciduous trees was less important. However, in cities with temperate and hot climates, dense shade on all surfaces reduced annual space cooling costs by 53–61% and peak cooling loads by 32–49%. Moreover, wind reductions were found to be beneficial in cold climates though in more temperate climates, they could be counterproductive if the vegetation was not strategically placed. For example, in Salt Lake City, a 50% wind reduction lowered annual heating costs by 8% whereas it increased annual cooling costs by 11% because of the obstruction of summer breezes. The conclusion was that the effects of vegetation could be positive or negative. For this reason, it is necessary to have an in-depth knowledge of the plant species as well as of the local climate [53].

These research studies coincide in affirming that the site climate, the tree species at the location, and number of trees in relation to the surface area are all factors that affect the energy consumption of nearby buildings.

3.3. Green roofs

Conventional building roofs are impermeable gray surfaces that contribute to the heat island effect in cities and increase flooding problems. Green roofs are feasible solutions for multi-story buildings, single family residences, commercial buildings, and other constructions. They improve building energy performance as well as the environmental conditions of the surroundings.

Niachou et al. analyzed the thermal properties of green roofs and concluded that during the summer, such roofs helped to keep air temperatures low during the day and higher at night. However, they found that night-time ventilation kept temperatures low during the day as well as at night. Energy consumption in buildings with green roofs was found to be lower than those without such roofs, and could even be improved by natural ventilation during the summer [54].

Takebayashi and Moriyama analyzed the surface heat budget on green roofs and on high-reflection roofs for the mitigation of the urban heat island effect [55]. Hirano and Fujita demonstrated that in downtown commercial buildings with green roofs, it was possible to reduce electricity consumption and thus mitigate the heat island effect [9]. Kohler et al. used four roof prototypes (three green roofs and one blank roof) to measure the rainwater retention rate and the temperature in the inside of these roofs to analyze the thermal comfort improvement. The conclusion was that green roofs contributed to a better microclimate because of evapotranspiration that filtered the dust in the air and lowered the roof temperature. Thermal comfort also improved under such roofs because there was more mass, dry or wet substrate, and shading from plants. Besides improving the microclimate and the indoor climate, the retention of rainwater was another important advantage that resulted in a significant reduction in the rainwater input in the sewage system during rainfalls. This helped to stem the rising risk of flooding in many cities, due to a ground sealed by buildings, asphalt, and concrete.

As a practical example, Kohler et al. studied the Potsdamer Platz in downtown Berlin, where 100% of the rainwater is evaporated or used for toilet flushing on the building site. Green roofs on city buildings were found to retain rainwater and generate a cooling effect, thus reducing flood risk and improving the urban microclimate. Moreover, the roofs also retained pollutants, which improved the quality of rainwater. This in turn reduced the entry of air borne pollutants into lakes and rivers during rainfalls and reduced the load in the sewage network [56].

Interestingly, despite the considerable amount of information on the microclimatic effects of greenery, there are very few authors that have quantitatively estimated these effects and integrated them into the design process. However, this is crucial so that scientific findings can have a practical application in the real world. An effort should thus be made to “translate” research results into the language of project design, where it can be used to benefit society.

3.4. Albedo

The temperature distribution in urban areas is affected by the urban radiation budget. The incident solar radiation on urban surfaces is absorbed and transformed into sensible heat. Roofs, building surfaces, streets, squares, etc. form a large mass where heat accumulates. This heat is then emitted with a time lag into the environment as long wave radiation. Furthermore, wave intensity depends on the percentage of surfaces visible to the sky and on the characteristics of materials, such as albedo, emissivity, thermal inertia, etc.

Taha analyzed the impact of a reduction in the surface and near-surface air temperature in relation to the increase in albedo and vegetation cover. This study demonstrated that the use of high-albedo materials decreased the solar radiation absorbed by building envelopes and urban structures. By keeping these surfaces cooler, the intensity of long wave radiation was reduced. The conclusion was that air temperatures on summer days can be lowered by as much as 4 °C, simply by modifying the surface albedo from 0.25 to 0.40 in a mid-latitude warm climate [8].

Taha also conducted a modeling study that analyzed the mesoscale meteorological and ozone air quality impacts of large-scale increases in surface albedo in southern California. With extreme increases in albedo, peak concentrations at 3 p.m. decreased by as much as 7%, i.e. from 220 down to 205 ppb (parts per billion) while the total ozone mass in the mixed layer decreased by up to 640 metric tons (4.7%). In reference to air quality, domain-wide population-weighted exceedance exposure to ozone decreased by as much as 16% during peak afternoon hours and by up to 10% during the daytime [57].

Rosenfeld et al. monitored various buildings to analyze the reduction in energy consumption for cooling by increasing the albedo. To measure the impact of white roofs and walls, these authors monitored the cooling energy use of a house and two school bungalows. The house was monitored in its original condition to obtain pre-modification data. At a school site, one of the two school bungalows was used as a control site and remained white roofed and walled all summer. The study was of two buildings. The first building remained white roofed and walled all summer, whereas the second was simultaneously monitored in three conditions: (i) unpainted metal roof and yellow walls; (ii) brown roof and brown walls; and (iii) white roof and white walls. The results obtained showed that a higher albedo in a single building produced 20–40% direct energy savings, and that the indirect effects of wide-scale albedo changes could nearly double the direct savings [44]. A study conducted by Bretz and Akbari achieved cooling energy savings of 10–70% by applying high-albedo coatings to residential buildings in California and Florida [58].

3.5. Pavements

The finishing materials of urban ground surfaces also have a major impact on the heat island effect. For example, in an urban layout in a conventional grid design, sidewalks occupy roughly 16%

of the ground surface. This percentage can be as high as 23% in rectangular sections typical of social housing complexes. Important factors to be considered are the following: (i) the horizontal surface exposed to solar radiation; (ii) the absorptance (ratio of the amount of radiation absorbed by a surface to the total radiation incident upon it); (iii) the generally high thermal capacity of the materials used.

Doulos et al. studied 93 pavement materials, commonly used in outdoor urban spaces to achieve lower ambient temperatures and thus fight the heat island effect. They observed variations in the mean daily temperature, mainly caused by the differences in the albedo factor of each material. It was found that rough and dark-colored surfaces (made of "hot materials") tended to absorb more solar radiation than the smooth, light-colored and flat surfaces (made of "cold materials"). Cold materials are thus preferable in urban environments with a hot climate whereas hot materials should be used in areas with a cold climate [59].

On the other hand, Scholz and Grabowieckiet conducted a review on novel materials, as permeable and porous pavement systems, as a part of storm water management system. This technique intends to manage the runoff in urban areas. The water collected by the pavement is discharged into a sustainable drainage system later. A permeable pavement system is composed typically by (from lower to upper): native sub-grade, geotextile (optional), base, bedding layer and permeable paver unit with drainage cells. The application of the described system encompasses vehicular and pedestrian access, slope stabilization and parking, among other uses. The use of permeable pavement systems is being established among engineering techniques, although more research is needed [108].

4. Planning strategies for the mitigation of the heat island effect (II):urban design

The distribution of urban buildings and structures in a city affects the formation of the urban heat island since this distribution can determine the absorption of solar energy and the formation of wind streams. The performance of an urban area in regards to solar radiation and air flows between buildings determines its contribution to the dispersion of suspended particles and of polluting gases. The urban response to solar radiation and air flows can be controlled by means of urban design [60]. Optimal designs can reduce energy consumption and CO_2 emissions, which can counteract the negative effects of the heat island [61].

According to Yamaguchi et al. an effective design/planning of city neighborhoods, the distribution of buildings, and energy-consuming equipment can achieve a reduction of 60–90% of the current CO_2 emission by the middle of the 21st century [62].

Liu et al. focused on the concept of eco-efficiency (an environmental strategy to reduce the impact of a product or service by increasing the efficient use of resources) and discussed aspects of urban design that were associated with it. They concluded that if more compact cities were designed, this could increase eco-efficiency [63]. This opinion is shared by Mindali et al., who also found that an increase in urban density can lead to a corresponding reduction in energy consumption [64].

Svensson and Eliasson analyzed variations in air temperature as well as energy consumption, depending on the construction typology (urban dense, multifamily, and single houses). Their results showed that the coldest zones were located on the outskirts of the city and that thermal stress and comfort were higher within the densely built-up category. In fact, due to local climate variations, a household within the densely built-up category was found to use 11–20% less energy on a yearly basis than a suburban one [65].

Larivière and Lafrance analyzed how electricity consumption was affected by a series of variables related to age, temperature, density, electrical heating, standardized land wealth, planning leisure and culture expenditure per habitant, etc. The results of the study showed that urban density was the only variable whose increase led to a reduction in electricity consumption [66]. Ratti et al. analyzed the effects of urban design on building energy consumption. They found that depending on urban design, the energy performance of buildings can vary by 10% [67]. However, other authors estimate a relative increase in energy consumption of up to 30% [99].

4.1. Urban design and solar radiation

Urban areas are characterized by many types of surface (building façades, pavements, roofs, etc.) which absorb short wave solar radiation and subsequently reflect it more slowly with a longer wavelength during the night. These long wave radiations are retained by suspended particles and combustion gases. The capturing of solar radiation as well as light exploitation and protection systems through urban design are important energy-saving strategies to replace conventional fossil fuels, and thus reduce environmental pollution and the urban heat island effect [68,104]. Baker and Steemers devised a procedure to evaluate the effects of shading systems on cooling loads [69].

Tregenza described a method for estimating mean illuminance on the working plane. He presented an example and values typical of window transmittance with louvres, canopies, and light shelves. Accordingly, the illuminance from windows that are shaded from direct sunlight can largely depend on the light reflected from the ground and by other buildings, thus altering electricity consumption for lighting [70].

On the other hand, changes in the building geometry, design, and orientation can affect solar access [71]. According to Mesa et al. the optimum ratio of separation between buildings and their heights is between the 2/3 and 1 in relation to the height of the same. The resulting urban high density morphology would enable obtaining all interior spaces to reach minimum levels of natural illumination intensity and quality [72] (see Fig. 2). In this line, Leveratto showed that buildings with more shade have façades with a less favorable orientation. It was found that when building form was modified, this could reduce impacts on the surroundings and increase the thermal comfort of the buildings [73].

Compagnon analyzed the effects of building geometry, design, and orientation in relation to the potential of building façades and roofs for capturing sunlight and using it for energy. The result was that over 30% of the area of the façade and roof was found to be suitable for applying passive solar techniques and over 50% for active solar techniques [74]. Yun and Steemers analyzed the implications of the urban surroundings for the design of photovoltaic and conventional building façades. In this study [75], Photovoltaic (PV) thermal and electrical models are integrated into the existing LT model to explore the energy and environment performance of a ventilated PV integrated passive design in the urban context. The analysis reveals that PV integration into a building is not necessarily constrained to orientation of urban form. Over 80% of the corresponding maximum PV output is expected in Oslo, Cambridge, and Milan when a PV panel's orientation is within a 60° of deviation from due south.

Cheng et al. examined the relation between built forms, density, and solar potential. This study comprised the solar simulation of eighteen generic models, each representing a particular combination of building form and density. The four built forms corresponded to different horizontal and vertical layouts, either uniform or random. Densities were examined in two ways, i.e. plot ratio and site coverage. The best designs were found to be those with randomness in the horizontal layout, randomness in the vertical layout, and low site coverage [76] (see Fig. 3).

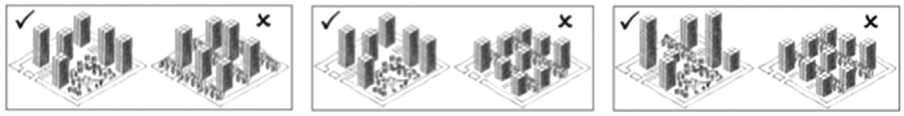


Fig. 3. (a) Low site coverage is preferable. (b) Vertical randomness is preferable. (c) Horizontal randomness is preferable [76].

Kristl and Krainer conducted the energy evaluation of the urban structure and dimensioning of parcels using the iso-shadow method[5]. For low buildings ($H=6$ m), the results showed that it was more logical for the building to have an N–S orientation. For medium-high and high buildings ($H=12$ m and y $H=36$ m, respectively), there was no preferred orientation. When buildings of the same height and orientation but different widths were compared, the distances between buildings slightly increased with the building width. Consequently, a larger plot was necessary. This was more evident in N–S oriented buildings. This increase in the size of the siting was more pronounced in buildings with heights of 12–24 m than in buildings with heights of 24–36 m. The results showed that an increase in the width of the buildings reduced the influence of the orientation for low buildings. Therefore, the width and height of the building was found to have a substantial influence on the size and design of the building site [77].

Krüger et al. monitored a residential building from January to August 2006 to establish variations in cooling energy consumption for aspect ratios (H/W) and street axis orientations. When three-dimensional density was high, N–S streets with high aspect ratios allowed for mutual shading of building façades and glazed openings, and reductions in cooling loads. Wide streets with an E–W axis and with north/south-facing building façades were found to allow for relatively low cooling loads even without mutual shading [78].

As reflected in the previously described studies, various authors have addressed the problem of solar access in obstructed and densely built-up environments. Their studies provide design guidelines or methods that guarantee solar access [79–81].

4.2. Urban design and air flow

The combination of high buildings and narrow streets that entrap hot air and reduce the airflow generates low-speed winds, which do nothing to disperse suspended particles and polluting gases, but rather generate the heat island effect [82]. According to Ratti et al.,the maximal dispersion of pollutants requires maximum turbulence. For example, the dispersion of pollutants from traffic in urban areas requires a maximum turbulence and vertical transport – and therefore high values of aerodynamic roughness. In order to increase roughness, there should be a number of tall buildings scattered within the urban texture. These authors also suggest that to control the wind and turbulences at street level, it is best to orthogonally orient buildings towards the predominant winds [83].

Generally, wind measurements in urban areas show a reduction in mean velocity (thus, reinforcing the heat island effect) and an increase in turbulences when they are compared with those in open spaces [84]. In an isolated building, the separation of the air flow above and behind the building produces a pressure difference, and thus a drag force over the building. The turbulence increases near to and on the leeward side of the building. The same characteristics in the flow around an isolated object can also be observed in the case of a group of buildings. There are different types of interference stemming from the space between buildings [85]. Isolated buildings have an isolated roughness flow regime. However, when there is an array of buildings, the regime changes to a wake interference flow with secondary flows in the street canyon space. At even greater H/W and density, there is a transition to a skimming flow regime where the bulk of the flow does not enter the canyon. All of these flow regimes depend on urban geometry [86].

4.2.1. Roughness and air flow

Various authors have proposed methods to determine the roughness length value (connection between the wind and drag force). Historically speaking, the conventional method is based on wind profile data observed on a sufficiently high mast [87]. Recently, huge 3D databases and powerful computers have been used to calculate the roughness length [88]. The algorithms used are based on the drag force over individual buildings and the interference between air flows around the buildings [89]. Numerous methods have been used to estimate urban aerodynamic roughness [90,91].

4.2.2. Urban street canyons and air flow

High buildings generate multiple horizontal reflections of the radiation received, which increase the probability that this energy will remain on the ground surface. This is known as the canyon effect. The roughness length is essential to determine the air flow over urban canyons. The problem of describing the wind in the canyon has been addressed in different ways. For example, Riain et al. and Norstrud et al. performed simulations with computational fluid dynamics techniques [92,93], whereas Kastner-Klein and Plate, Pavageau and Schatzmann used scale models in wind and water tunnels [94,95].

When considering air flow and pollution dispersion on an individual scale in streets, the geometry of canyons (height/width ratio in the canyon) is the main input required to provide the flow and street concentrations of traffic pollutants [96–98]. Stromann-Andersen and Sattrup calculated that canyon geometry had an impact on the total energy consumption of up to 30% for commercial buildings and 19% for residential buildings [99]. In deep street canyons, variations in wind speed can be important and produced significant temperature differences over the street canyon (approximately 5° higher) than inside of it. This temperature difference has a great impact on the cooling loads [100]. When a deep canyon (H/W=9.7) was compared with a shallower one (H/W=0.6), the results showed that during the day, the deep canyon was colder than the shallower one. For this reason, in the summer, the deeper canyon had more favorable temperatures than in the winter. In contrast, the shallower canyon was more comfortable in the winter since it permitted solar access [101].

Such methods use different parameters to characterize urban winds. Steemers et al. used urban porosity and geometric quantities to evaluate the response of wind to texture [102]. Similarly but in the context of solar radiation [103], Ferrant and Cascella presented a final design proposal for a new housing development in the peri-urban context of Tricase, a town in southern Italy. The objective was to provide the buildings with access to solar radiation and be able to analyze the effect of wind direction on

[5] Iso-shadows represent the ratio of incident solar radiation on a building or land to unobstructed solar radiation received at the same location and expressed as a percentage. Iso-shadows are contours, marking the areas which receive the same percentage of solar radiation. The quantity of incident radiation is divided into 10% steps, from 0% to 100%, during a selected period of time (day, month, or year). They are used to determine the geometry and site of a building in relation to other buildings and their impact on the quantity of solar radiation at the chosen position.

the site [104]. Bruse and Fleer studied how air flows varied in the presence of trees [105].

Grosso et al. used simple ratios of land occupation and building density to evaluate the natural ventilation potential of buildings [106]. Croxford et al. used a"space syntax" model to measure urban pollution at the scale of the street segment [107].

5. Conclusions

Cities consume more energy than rural areas because of activities such as the heating and cooling of buildings, urban transportation, commercial and industrial activities, etc. This high level of consumption is influenced by the urban heat island effect. It is possible to apply a series of strategies that mitigate the effects of the heat island in the design phases of urban planning. Based on the overview of recent research provided in this article, the following conclusions can be derived.

(1) Generally speaking, there are three elements to be considered in urban planning, which have a major impact on temperature variation in the city on a local scale: buildings, green spaces, and pavements.
(2) The distribution of the buildings and urban structures in a city affect the formation of the urban heat island, since this distribution usually determines the absorption of solar radiation and the formation of air flows.
(3) The combination of high buildings and narrow streets that entrap hot air and reduce the air flow generate low-velocity winds that do not disperse suspended particles and polluting gases. This is conducive to the heat island effect.
(4) To counteract or mitigate the heat island effect, if measures are applied to urban elements affecting temperatures on a local scale, various parameters can be used to evaluate the potential impact produced by the modification of urban morphology on energy consumption, and thus reduce CO_2 emissions into the atmosphere.
(5) The application of measures to counteract or mitigate the heat island effect depends on a wide range of factors, some of which can be incorporated into planning strategies, whereas others are outside the scope of the use and geometry of spaces.
(6) The research studies analyzed conclude that parks and green spaces help to mitigate the heat island effect and reduce energy consumption for cooling buildings in the summer, besides stabilizing the fluctuation of temperatures caused by building materials. However, it is not clear how the characteristics of the park affect the formation of the cold island. As a result, certain authors affirm that depending on the climate of the site, the tree species, and the number of trees in relation to the surface area, parks and green spaces can produce an increase or reduction in the energy consumption of nearby buildings.
(7) Vegetation cover improves the energy performance of buildings as well as the environmental conditions of the surrounding area.
(8) An effort should be made to systematize all current knowledge concerning the effects that greenery has on the urban microclimate. This would greatly facilitate the work of architects and engineers in charge of urban design.
(9) If the albedo coefficient is increased, it is possible to achieve direct energy savings of 20–70%.
(10) The geometry of urban canyons has an impact on the total energy consumption of up to 30% in commercial buildings and 19% in residential buildings. In deep canyons, wind speed variation can be important, resulting in substantial temperature differences (approximately 5° higher) over the canyon than at street level.
(11) The optimization of urban design/planning in relation with the energy consumption of buildings allows savings of up to 30%.

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